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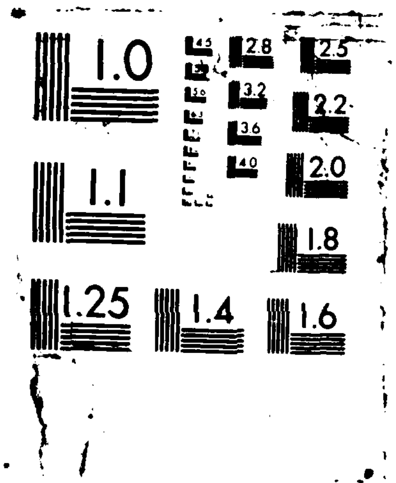
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Numerical simulation was used to explore the process of transition that a flow undergoes in changing from a laminar state to a turbulent state. The effort concentrated on three relatively simple flows for which extensive databases exist; these are the plane channel, curved channel, and flat plate boundary layer flows. Significant results were produced for all three cases.

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on

Simulation of Laminar-Turbulent Transition in the Vicinity of a Wall

Work done under
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I. Introduction

The goal of this research was to use the techniques of numerical simulation to explore the processes of transition that a fluid flow undergoes in changing from a laminar state to a turbulent state. The effort concentrated on three relatively simple flows for which the extensive experimental databases exist; these are the plane channel, curved channel, and flat plate boundary layer flows. Significant results were produced for all three flows.

Work on each flow was carried out by a graduate student under the direction of the principal investigators. Important assistance was provided by Dr. Philippe R. Spalart of NASA-Ames Research Center. Work on the plane channel flow by Bart Singer has been completed and a report on this work has been submitted to AFOSR (1). Similarly, the effort on the curved channel carried out by Warren Finlay is finished and a report has been sent to AFOSR (2). Work on the plane boundary layer by Kyung Soo Yang is essentially finished and the report is being written at the present time (3); it will be submitted shortly. Several conference and journal papers based on the work have also been published; these will be referenced below.

As detailed reports on each part of the work have been written, only brief reviews will be given here. This will be done for each flow separately as they were treated nearly independently.

II. Plane Channel Flow

The investigation began with a study of the stability of plane Poiseuille flow. This flow is known to undergo transition at Reynolds numbers far below the critical value predicted by linear theory due to a nonlinear secondary instability mechanism. To simulate these processes, cases in which the initial conditions consisted of a combination of the parabolic laminar flow profile, a two-dimensional Tollmien-Schlichting (TS) wave (to simulate the finite amplitude disturbance) and low-amplitude three-dimensional random noise (to simulate the random disturbances) were run. These were the first simulations that did not force particular three-dimensional modes; the simulation was allowed to choose which modes to amplify. We found, in accord with the theory, that subharmonic modes grow at low TS amplitudes and that a mixture of subharmonic and fundamental modes grow at larger TS amplitudes; the results were published in Ref. 4.

We next studied the effect of streamwise vortices on this flow in an attempt to explain discrepancies between experiments and theory. The best experiments (by Nishioka's group) found the K-type (fundamental) transition mechanism to dominate under circumstances in which Herbert's theory predicts that the H-type (sub-harmonic) mechanism should dominate. Inspection of the data showed spanwise nonuniformities in the experimental flow that could be due to the presence of streamwise vortices. Simulations which included streamwise vortices of the strength required to produce the experimental velocity profiles were made and showed that, for the length of channel used in the experiment, the K-type mechanism does indeed dominate. The simulation also predicts that if the experimental fetch had been twice as long, the H-mechanism would have been found to dominate. This work was published in Ref. 5.

Finally, we studied the effect of flow oscillations on transition in the plane channel flow. These are believed to be important in gas turbines and may be a way of enhancing heat transfer. First, the effect of the unsteadiness on the growth rate of the two dimensional Tollmien-Schlichting (TS) waves was studied. Our results agree with those of Kerczak but disagree with those of Grosch and Salwen; the oscillations are stabilizing at all but a limited range of frequencies. An appropriate non-dimensional frequency characterizing the flow over a range of Reynolds numbers was found; it is the frequency divided by the frequency of the least stable TS wave. The mechanism of three-dimensional instability was found to be the same as that in the non-oscillating case. This work was published in Ref. 6.

As a tool for studying energy transfer among the various modes, a method for computing the transfers among triads of modes was developed and published in Ref. 7.

III. Curved Channel Flow

A proposed explanation of the poor agreement between experiment and computation of the heat transfer on turbine blades is the effect of curvature. Curvature is known to have a significant effect on turbulent flows. To begin investigation of this issue, we chose the simplest curved flow, the curved channel, as the next flow to study. This choice was also influenced by the existence of many results for flows related to this one--the plane channel flow (see above) and the Taylor-Couette flow in an annulus with rotating walls.

This part of the work began with the computation, on the basis of linear stability theory, of the growth rates of instabilities in this flow; earlier authors gave only the neutral stability curve. In agreement with previous work, it was found that the critical Dean number is 36; the instability leads to the formation of finite-amplitude streamwise (Dean) vortices similar to the Goertler vortices found in curved boundary layers. The properties of fully developed Dean vortices were investigated as a function of the Dean number and vortex spacing. A process of vortex bifurcation that limits the range of vortex spacings observable in experiments more narrowly than linear stability theory would suggest was discovered. This process, in which a single Dean vortex spontaneously becomes a pair of similar, but smaller, vortices may have been observed experimentally recently. We found that a non-linear theory of the Landau type works well only for closely spaced vortices. For the more widely spaced vortices likely to be observed in an experiment, the non-linear theory and direct simulation results differ by a factor of two in the vortex strength. This work was published in Ref. 8.

We then investigated three dimensional instabilities of this flow by introducing perturbations sinusoidal in the streamwise direction into fully developed Dean vortex flow and simulating the response. The results were rather surprising. The flow first becomes unstable to three-dimensional motions at a Dean number not much higher than the critical Dean number of the laminar flow. These long-wave instabilities result in the Dean vortices becoming wavy. Although this state is similar to the one produced by the secondary instability of the Taylor-Couette flow, the growth rates of these modes are so low that at least a 360^{o} turn would be required for the fully developed state to be reached. These modes will probably not be observed in an experiment; the experiment on this flow by Kelleher does not show them. Furthermore, the growth rate of this instability increases with Dean number for only a short while after which it decreases.

When the Dean number reaches the vicinity of 70, another mode of three-dimensional secondary instability arises. The wavenumber of this instability is much higher (by a factor of 20) than that of the instability described in the preceding paragraph; the wavelength is only slightly larger than the distance between the Dean vortices. This instability has much higher growth rates than the long-wave modes described above. It leaves the vortices nearly straight but their shapes oscillate with streamwise position; we call the end-state of this instability twisting vortex flow to distinguish it from the undulating vortex flow described above. Recent experimental photographs for rotating channel and curved boundary layer flow provide evidence for the existence of twisting vortices. This work has been submitted for publication in Ref. 9.

IV. Flat Plate Boundary Layer

The boundary layer on a solid surface is both the flow of greatest technological importance and the most studied flow. A great deal of data exist for both the fully turbulent and transitional cases. However, the two-dimensional instability in this flow is a sensitive function of both wavenumber and Reynolds number. As the growth rate of the three-dimensional instability depends strongly on the amplitude of the two-dimensional modes, the transitional behavior of this flow is very sensitive to both the governing parameters and the initial (or upstream) conditions.

The growth of the thickness the boundary layer with downstream distance makes the assumption of periodicity used in the simulations described above even more questionable. This difficulty can be avoided by treating the time-developing flow (the boundary layer on a suddenly started flat plate) rather than the spatially developing one. Unfortunately, the laminar profiles are different (an error function vs. the Blasius profile). As the stability characteristics (including the critical Reynolds number) are sensitive to the profile, results for the temporally developing flow would be very difficult to compare with experiment. For this reason, the temporal problem and streamwise periodic boundary conditions were adopted but forcing terms that cause the laminar velocity profile to have the Blasius form were added to the equations. In this way, one has the best of both approaches.

The first work on transition in the flat plat boundary layer was very similar to the first work on the channel flow. The initial conditions contained finite-amplitude two-dimensional TS waves and random disturbances in addition to the laminar flow. It was found that subharmonic mechanisms dominate at low TS wave amplitudes and fundamental modes become more important at high amplitudes. A paper on this work was published in the Journal of Fluid Mechanics (10).

The effort then concentrated on the simulation of transition on a decelerating plate. First, the laminar flow on a decelerating plate was simulated; this established the base flow for the transition simulations. Then transition simulations were made. Unlike any previous simulations, the initial conditions contained no organized disturbances, only the laminar flow and random perturbations. The unstable modes grew out of the noise, resulting in patterns different from those found in ribbon-induced transition. The detailed structure of the flow depends on the random number seed used to generate the initial conditions. Three-dimensional lambda-shaped vortices occur in the flow but the pattern is most often either oblique to the flow direction or scattered. The reason for these patterns was traced to the fact that, in this flow, more than one Tollmien-Schlichting wave grows to significant amplitude. At least one of the dominant waves is usually oblique and this produces the observed patterns. These results are in good agreement with the experiment of Gad-el-Hak et al.

Finally, simulations of a single lambda vortex in the late stages of transition were made. Simulated visualizations are in good agreement with those of Hama and Nutant. Detailed observations of the patterns of vorticity have given new insight into the nature of the late stages of transition.

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